Sealing, Amendment, and Rain Intensity Effects on Erosion of High-Clay Soils

José Miguel Reichert,* L. Darrell Norton, and Chi-hua Huang

ABSTRACT

The physicochemical composition of and processes acting on the soil-fluid interface determine detachment and transport of soil particles by erosive forces at the surface during rain. It is hypothesized that fluidized bed combustion (FBC) bottom ash and soil surface condition change the relationship between rain intensity and runoff and sediment yield. On small erosion pans, aggregates from five clayey soils (Alfisol, Oxisol, Ultisol, and Vertisols) with distinct swelling and flocculation characteristics were subjected to simulated rainfalls of 74, 39, and 107 mm h⁻¹ for 90, 30, and 30 min, respectively. This rain sequence was applied on freshly tilled (FT), dried-crust (DC) and wet-crust (WC) soil. Fluidized bed combustion bottom ash was spread on FT soil at a rate of 5 Mg ha⁻¹. Power functions described well sediment yield as a function of rain intensity, with exponents of 1.97 for FT, 1.74 for DC, and 1.72 for WC; thus as the soil sealed and consolidated, rain intensity influenced the erosion rates less. Dried-crust was the most erodible surface for half of the soils. Clay shrinkage disrupted aggregates and preformed crusts, whereas rewetting caused differential swelling and raindrops pitted the soil surface. Runoff decreased from FT to DC, but no increase was observed from DC to WC. Smectitic and illitic soils had a longer-lasting positive effect of FBC bottom ash on reducing soil and water losses. For the highly smectitic Vertisols, FBC bottom ash was effective on reducing erosion even after 552 mm of rain. Kaolinitic soils were more stable, generating lower runoff and soil loss rates.

At the soil surface the complex partitioning of rainfall into infiltration, surface retention and detention, and runoff occurs. Soil erosion also is a surface process and is dependent upon the characteristics of the soil-fluid interface as well as on the dynamic interactions between the phases. During rain, soil aggregates are disintegrated mechanically by the raindrop impact and chemically due to dispersion, thus causing surface sealing. In interrill areas, sealing is a dynamic process that significantly influences infiltration, runoff, and erosion (Duley, 1939; Bradford et al., 1987; Le Bissonnais et al., 1989; Moore and Singer, 1990; Roth and Helming, 1992; Le Bissonnais and Singer, 1993). Most erosion studies were conducted on FT soil under a single rainfall event. Erosion from already crusted soils has received less attention (Roth and Helming, 1992; Huang and Bradford, 1993; Zhang and Miller, 1993).

During a rain event, erosion rates decrease with time due to densification or consolidation and loss of readily transportable sediments (Miller, 1987). Densification and increased soil shear strength or cohesion with surface sealing decrease soil detachment (Bryan et al., 1989), increase runoff (Roth and Helming, 1992), and decrease sediment concentration (Miller and Baharuddin, 1987). However, formation of incipient rills may change the erosion process and increase sediment yield, depending upon the soil slope (Huang and Bradford, 1993), soil type (Reichert, 1993), and duration of the rain (Poesen and Govers, 1985).

Between erosion events, soil densifies due to time and drying stresses, causing increased stability. It is generally considered that FT soil is the most erodible. Although this holds for may situations, there are recent experimental evidences that processes occurring with drying–wetting cycles may indeed increase soil erodibility (Huang and Bradford, 1993; Zhang and Miller, 1993). Shrinking of clays upon drying weakens the cohesive forces within the crust, rendering it susceptible to pitting by raindrops (Hardy et al., 1983), and new aggregates with possible lower stability are formed (Bradford and Huang, 1992). In addition, rewetting may cause differential swelling, creating failure planes and slaking due to entrapped air within the aggregates.

Mechanical and chemical processes are complementary in surface sealing (Levy et al., 1986). Low electrolyte rain causes chemical dispersion and swelling of clays. Addition of electrolytes with surface application of phosphogypsum (Levy et al., 1986; Miller, 1987; Norton et al., 1993) increases infiltration and reduces sealing and erosion. The positive effect is attributed to increased electrolytes and ionic strength in the soil solution and in the runoff. However, gypsum-like materials, such as FBC bottom ash, are of mixed nature, being both a source of electrolytes and of alkalinity. The effect of such materials on erosion has received little attention (Norton et al., 1993).

Abbreviations: FT, freshly tilled; DC, dried-crust; WC, wet crust; CFC, critical flocculation concentration of electrolytes; FBC, fluidized bed combustion; Qₛ, sediment yield; Qᵣ, runoff rate; R, rain intensity; S, slope; Ω, stream power.
The process of erosion can be divided into detachment, transport, and deposition subprocesses. Sediment eroded from a field is the result of complex interactions among those subprocesses. In interrill areas, the sediment is detached by raindrop impact and transported by the shallow flow. Therefore, the interrill erosion has been estimated as a function of rain intensity (Rose et al., 1983), runoff or stream power (Rose et al., 1983; Huang and Bradford, 1993), and the combination of both rain intensity and runoff. It is incorrect to equate sediment yield to detachment rate, because the amount of sediment delivery may be limited by the transport capacity (Huang and Bradford, 1993). If the soil surface condition or the chemical dispersibility changes, which will cause changes in the detachability of sediments, different relationships among sediment loss, rain intensity and runoff (or stream power) should be expected. The overall objective of this study was to determine the effects of three surface conditions from a sequence of three rain events with drying between the second and third event, three rain intensities (medium, low, and high), and Purdue Univ. FBC bottom ash on runoff and sediment yield from five high clay surface soils.

MATERIALS AND METHODS

Soils used in this study, along with selected properties, are listed in Table 1. A detailed listing of soil properties for these soils are presented in Reichert (1993). Soil materials, sieved through an 8-mm opening, were packed into an erosion pan to a depth of 5.5 cm. The erosion pan was 32 cm wide, 45 cm long, and 20 cm deep. The pan had a 14.5-cm bottom layer of gravel to allow free drainage of the percolating water. For the swelling soils, the packed soil was not flush with the pan's surface, allowing space for upward swelling.

On air-dried soil, right before the rain, FBC bottom ash from the Purdue Univ. power plant was surface applied at a rate of 5 Mg ha⁻¹. The FBC bottom ash was composed primarily of anhydrite (CaSO₄, 73%), lime (CaO, 23%), portlandite (Ca(OH)₂, 3%), calcite (CaCO₃, 1%), gypsum (CaSO₄·2H₂O, traces), and oldhamite (CaS, traces). The elemental chemical composition was 55.0% CaO, 40.5% SO₂, 4.8% SiO₂, 1.1% Al₂O₃, 0.8% Fe₂O₃, 0.3% MgO, and small amounts of Na₂O, K₂O, P₂O₅, and TiO₂. Total dissolved salts were 4700 mg L⁻¹, the electrical conductivity of a 1:1 FBC bottom ash/water solution was 11 dS m⁻¹, and pH was 12.5. Thus, the mixed nature of the FBC bottom ash indicates that it is a source of electrolytes and of alkalinity.

We used a rain sequence of 74, 39, and 107 mm h⁻¹ for 90, 30, and 30 min, respectively. The rain sequence of medium to low-high intensities was also used by Meyer and Harmon (1984) and Huang and Bradford (1993). The rain intensities were changed instantaneously during the rain by using a programmable rain simulator (Neibling et al., 1981) equipped with 80-100 Veejet nozzles, with a kinetic energy of about 75% of the energy of natural rain (Meyer and McCune, 1958) for a given intensity.

After the first rain on the initially air-dried soil, the soil was allowed to dry for 4 to 5 d, until the surface was dry and cracking (shrinking) was evident. Then, the same rain sequence was applied. The next day, while the soil was still wet, the soil was once again subjected to the same rain sequence. These three surface conditions are designated FT, DC, and WC, respectively. During all events, the soil surface was adjusted to a 5% slope. When considerable erosion was observed at the upper end of the plot, the pan was re-adjusted to maintain 5% slope. Sediment loss and runoff (including splashed water and sediment directly on the collecting trough) were measured every 5 min, but only the last 20 min of each event were compiled herein, when a dynamic steady state had been achieved. The experiment was randomized for soil and FBC bottom ash amendment, with two replications. The experimental design was a completely randomized split block. Linear and nonlinear regression were determined using SAS procedures (SAS Institute, 1988).

RESULTS AND DISCUSSION

All soils had clay texture (Table 1), but they encompassed a wide range of clay mineralogies (Fig. 1), from oxidative to highly smectitic, and critical flocculation concentrations (Table 1). All soils, except for the Cecil (clayey, kaolinitic, thermic Typic Kanhapludult) eroded, had reduced erosion with FBC bottom ash under high intensity (110 mm h⁻¹) rainfall (Reichert, 1993).

Only results for the last 20 min of each rain (steady-state conditions) were analyzed. The first rain on each surface condition wetted and sealed (or resealed) the soil. For the second and third events, the first 10-min period partially reflected runoff characteristics of the previous rain event. Differences in soil loss and runoff at steady state are mainly due to processes occurring during the wetting-drying cycles. Because water was lost from the pan both by runoff and splash, the difference between rainfall and runoff can not be equated to infiltration, which was not explicitly measured.

Sediment Delivery, Runoff, and Rain Intensity Relationships

Regression analysis showed that power functions (Table 2) described well sediment loss rate (Qₛ) as a function

**Table 1. Soils studied and selected soil properties.**

<table>
<thead>
<tr>
<th>Soil</th>
<th>Classification</th>
<th>Clay</th>
<th>Silt</th>
<th>CEC†</th>
<th>CFC†</th>
<th>Fe₂O₃†</th>
<th>SA†</th>
<th>COLE†</th>
<th>MWD†</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cecil eroded</td>
<td>Typic Hapludult</td>
<td>406</td>
<td>174</td>
<td>8.5</td>
<td>-2</td>
<td>27.8</td>
<td>0.011</td>
<td>0.57</td>
<td></td>
</tr>
<tr>
<td>Molokai</td>
<td>Typic Eutrotex</td>
<td>420</td>
<td>336</td>
<td>19.2</td>
<td>0.5</td>
<td>125.8</td>
<td>97.9</td>
<td>1.20</td>
<td></td>
</tr>
<tr>
<td>Grey Clay</td>
<td>Udic Chromustert</td>
<td>460</td>
<td>262</td>
<td>40.8</td>
<td>0.5</td>
<td>12.6</td>
<td>104.2</td>
<td>0.063</td>
<td>0.32</td>
</tr>
<tr>
<td>Horrville</td>
<td>Mollic Ochraqualf</td>
<td>566</td>
<td>370</td>
<td>33.5</td>
<td>3.5</td>
<td>14.6</td>
<td>94.4</td>
<td>0.037</td>
<td>4.02</td>
</tr>
<tr>
<td>Irving Clay</td>
<td>Typic Pelludult</td>
<td>602</td>
<td>276</td>
<td>68.8</td>
<td>1.5</td>
<td>31.4</td>
<td>401.7</td>
<td>0.155</td>
<td>0.19</td>
</tr>
</tbody>
</table>

† CEC = cation exchange capacity; CFC = critical flocculation concentration of electrolytes with gypsum; Fe₂O₃ = iron extracted by ammonium oxalate; SA = specific surface area; COLE = coefficient of linear extensibility; MWD = mean weight diameter of air-dried aggregates by wet sieving.

Negligible.

° Flocculated without adding any extra electrolyte.

§ Negligible.
of rain intensity \((R)\) or runoff \((Q_w)\), and \(Q_w\) as a function of \(R\). Because \(R\) and surface condition were not randomized, there was some confounding between the two treatments.

Exponents \(b\) for \(Q_w = aR^b\) (Table 2) were very close to 1 for most soils and conditions, showing an approximately linear relationship between \(Q_w\) and \(R\). Quadratic polynomials (not shown) could be fitted for sediment concentration as a function of \(R\) or \(Q_w\), for most of the soils. As shown in Fig. 2, however, there was only a small increase in sediment concentration with increasing \(R\) for the Cecil soil, while for the Molokai (clayey, kaolinitic, isohyperthermic Typic Torrox) FT-FBC, there was a decreasing concentration with increasing \(R\).

The exponent of the power function \(Q_s = aR^b\) (where \(a\) and \(b\) are empirical parameters) was greatest for FT soil, suggesting that as the soil seals and consolidates, there is a lesser influence of \(R\) (or \(Q_w\)) on erosion. The FBC bottom ash treated soils had greater \(b\) than did the control, and differences in \(b\) among surface conditions were greater for FBC bottom ash than for the control. These results indicate that FBC bottom ash changed the relation between soil loss rate and \(R\). Among soils, Reichert (1993) observed that, for the control, the sandi-

Table 2. Regression analysis on sediment yield \((Q_s)\) and runoff rate \((Q_w)\) as functions of rain intensity \((R)\) for the studied conditions.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Condition</th>
<th>(n)</th>
<th>(\alpha)</th>
<th>(b)</th>
<th>(r^2)</th>
<th>(a)</th>
<th>(b)</th>
<th>(r^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C(^+)</td>
<td>FT(^+)</td>
<td>30</td>
<td>0.0009</td>
<td>1.99</td>
<td>0.53</td>
<td>0.462</td>
<td>1.06</td>
<td>0.94</td>
</tr>
<tr>
<td>C</td>
<td>DC(^+)</td>
<td>30</td>
<td>0.0034</td>
<td>1.65</td>
<td>0.52</td>
<td>0.533</td>
<td>1.05</td>
<td>0.94</td>
</tr>
<tr>
<td>C</td>
<td>WC(^+)</td>
<td>30</td>
<td>0.0052</td>
<td>1.55</td>
<td>0.65</td>
<td>0.697</td>
<td>1.00</td>
<td>0.95</td>
</tr>
<tr>
<td>FBC(^+)</td>
<td>FT</td>
<td>30</td>
<td>0.0006</td>
<td>1.93</td>
<td>0.64</td>
<td>0.691</td>
<td>1.37</td>
<td>0.82</td>
</tr>
<tr>
<td>FBC</td>
<td>DC</td>
<td>30</td>
<td>0.0011</td>
<td>1.85</td>
<td>0.50</td>
<td>0.606</td>
<td>1.01</td>
<td>0.93</td>
</tr>
<tr>
<td>FBC</td>
<td>WC</td>
<td>30</td>
<td>0.0007</td>
<td>1.94</td>
<td>0.97</td>
<td>0.624</td>
<td>1.02</td>
<td>0.98</td>
</tr>
<tr>
<td>C</td>
<td>FT</td>
<td>60</td>
<td>0.0007</td>
<td>1.97</td>
<td>0.72</td>
<td>0.232</td>
<td>1.19</td>
<td>0.81</td>
</tr>
<tr>
<td>FBC</td>
<td>DC</td>
<td>60</td>
<td>0.0021</td>
<td>1.74</td>
<td>0.54</td>
<td>0.578</td>
<td>1.03</td>
<td>0.93</td>
</tr>
<tr>
<td>FBC</td>
<td>WC</td>
<td>60</td>
<td>0.0022</td>
<td>1.72</td>
<td>0.45</td>
<td>0.659</td>
<td>1.01</td>
<td>0.97</td>
</tr>
<tr>
<td>C</td>
<td></td>
<td>90</td>
<td>0.0025</td>
<td>1.73</td>
<td>0.53</td>
<td>0.560</td>
<td>1.04</td>
<td>0.93</td>
</tr>
<tr>
<td>FBC</td>
<td></td>
<td>90</td>
<td>0.0008</td>
<td>1.91</td>
<td>0.68</td>
<td>0.378</td>
<td>1.10</td>
<td>0.80</td>
</tr>
</tbody>
</table>

\(\dagger\) \(n\) = number of data points. C = Control; FBC = Fluidized bed combustion bottom-ash; FT = freshly tilled; DC = dried-crust; WC = wet-crust. 
\(\ddagger\) \(r^2\) was calculated by linearly regressing the observed against the estimated \(Q_s\) or \(Q_w\).
Soils with more silt or clay were more sensitive to \( R \). Meyer (1981), using a similar rain sequence, observed a greater influence of \( R \) on \( Q_s \) for low-clay soils than for those with greater clay contents. The reason was not obvious, but he suggested that greater cohesiveness of clay soils slowed the rate of soil detachment and produced larger sediment that was more difficult to transport. The main difference between his and our study is that we used high clay soils that were either dispersive under rain and/or expandable with wetting, except the Cecil soil. Watson and Laflen (1986) also observed that the intensity exponent was apparently related to variables other than clay content. The \( Q_s \) was related to \( R \) by a power ranging from 1.0 to 2.4, with an average of 1.8, which is consistent with other empirically derived results (Meyer, 1981; Watson and Laflen, 1986; Meyer and Harmon, 1984). An analytic basis to this empirical relation is given by Huang and Bradford (1993).

Soil in interrill areas is detached by rainfall and flow shear. The detached soil is transported off the plot by splash and rain impacted flow. Huang and Bradford (1993) suggest that the sediment collected at the outlet is what has been transported and is not equal to what has been detached. Sediment deposition occurred particularly on the highly erodible smectitic soils (Grey Clay and Irving Clay), indicating a transport limiting condition. Runoff capacity to transport sediment can be estimated by its stream power (\( \Omega \)) as proposed by Bagnold (1966) and simplified by Huang and Bradford (1993) to \( \Omega = SQ_w \), where \( S \) is the slope and \( Q_w \) is the runoff discharge. Herein, slope was constant and \( \Omega \) changed only by changes in \( Q_w \). But, because \( R \) was linearly related to \( Q_w \) (or \( \Omega \)) to estimate \( Q_s \) provides similar results.

**Surface Condition and Erosion and Runoff**

Freshly tilled soil is usually assumed to be the most erodible condition. The surface condition with greatest sediment yield (Fig. 3) or total sediment loss was dependent upon the soil type and FBC bottom ash treatment. The FT soil was indeed the most erodible condition for smectitic (Irving Clay), smectitic/kaolinitic (Grey Clay), and oxidic (Molokai) soils. When FBC bottom ash was applied, FT was no longer the most erodible condition for Grey Clay and Molokai soils.

The DC was the most erodible condition for the kaolinitic Cecil (with and without FBC bottom ash, except FBC at 107 mm h\(^{-1}\) rain), oxidic Molokai (with FBC bottom ash, except at 107 mm h\(^{-1}\) rain), smectitic Grey Clay (with FBC bottom ash), and illitic Hoytville (fine, illitic, mesic Mollic Ochraqualf; without FBC bottom ash, except at 107 mm h\(^{-1}\) rain). Shrinking of clays upon drying generates failure planes on undisrupted aggregates and on preformed crusts. With rewetting, an increased supply of easily detachable particles is available for transport by overland flow. These dispersed particles may also enhance sealing on already sealed soils. On soils where DC was the most erodible condition, a mud-like surface layer was present. Interestingly, for some soils...
at a rain intensity of 107 mm h\(^{-1}\), DC was no longer the most erodible, suggesting that much of the muddy layer had eroded away. When the soil is highly smectitic and swelling, such as the Irving Clay, cracking and swelling, although very intense, seems not to be operative in increasing erosion. The tendency of the crust to weaken is possibly related to the linear extensibility of disaggregated <2-mm soil (Bradford and Huang, 1992). It is also interesting how the FBC-DC was the most erodible on three of the soils (Cecil, Molokai, and Grey Clay). Possibly, besides the aforementioned mechanisms, clay flocculated by FBC bottom ash and stable aggregates are available for transport in the subsequent rain event.

Crusts develop strength as their water evaporates. Surface tension forces draw particles surfaces into intimate contact (where H bonding, Van der Walls forces, and other short-range forces bond these particles together) and slightly soluble materials such as silicates, hydroxides, etc. are forced to particle-to-particle contacts by receding menisci and precipitated as semicrystalline cementing agents as drying takes place (Kemper et al. 1974). But at the same time, the soil surface generally shrinks to some extent and cracks develop at the weakest planes. Hardy et al. (1983) postulated that drying weakens the cohesion forces within the crust, rendering it susceptible to pitting by impacting raindrops and increasing the infiltration rates in subsequent storms. In this study, runoff rates (Fig. 4) and total water loss were always greater for DC and WC than for FT soil for any of the intensities, except for Cecil, thus indicating that a less permeable seal is formed due to slaking of cracked crust with rewetting. Further rain on the WC did not increase runoff. Roth and Helming (1992) also observed that crusts formed with repeated drying and wetting cycles tended to be more dense than a crust where the soil received the same amount of rainfall energy in one single event.

**Fluidized Bed Combustion Bottom-Ash Effect on Soil and Water Losses**

The physicochemical characteristics of and processes acting on the soil surface determine the forces resisting erosion and the bed shear at which erosion occurs. The effect of drying–wetting on erosion was discussed earlier. Our focus now is on the interaction between surface condition and applied FBC bottom ash.

The surface-applied FBC bottom ash on the air-dried FT soil decreased soil loss (Fig. 3) and water loss (Fig. 4), for all three intensities, except for Cecil eroded soil (at any surface condition). The Cecil eroded soil studied was highly flocculated, behaving quite differently than soil from Ap horizon, which is highly dispersible (Miller, 1987; Norton et al. 1993). For the highly weathered oxidic Molokai soil, FBC bottom ash reduced soil loss rate only for FT soil, having afterwards a detrimental effect for the DC condition. Considering the pH at CFC with FBC bottom ash and the net charge curves, Reichert and Norton (1993, unpublished data) observed that, for variable charge soils with small increase in negative charge when increasing the pH from point of zero salt
The effect to pH at CFC, the FBC bottom ash either decreased (Molokai) or had no effect (Cecil) on runoff and erosion. By contrast, for soils with greatest increase in negative charges, FBC bottom ash either increased or had no effect on runoff and erosion. Increasing pH enhances dispersion of variable charge clays by increasing negative charges. Also, in the short term, CaO, Ca(OH)₂, and CaCO₃ cause dissociation of organic functional groups of organic matter which in turn complexes Al in soil solution. Thus, Al in solution is reduced and Al on oxide and clay mineral surfaces is neutralized, further increasing negative charges and dispersion of soil particles. These could well be responsible for the non-effectiveness (Cecil FT, DC, and WC) and even increases (Molokai DC) in runoff and erosion with FBC bottom ash application.

For siliceous and swelling soils (Hoytville, Grey Clay, and Irving Clay), FBC bottom ash was effective in reducing soil loss even at the WC condition at 107 mm h⁻¹, i.e., after having received 552 mm of rain. The positive effect was more striking on the high-swelling Irving Clay soil. For the Irving Clay, reduced runoff with FBC bottom ash compared with the control was observed for all three surface conditions. For the illitic Hoytville soil, such an effect was observed up to the DC condition. Kemper and Noonan (1970) observed on gypsum-treated soil that raindrops and subsequent drying action rework and reorganize the soil crust into new geometries of clustered or individual particles, depending on whether the soil is largely Ca or Na saturated, respectively. Because surface-applied FBC bottom ash may be removed through dissolution and erosion from the soil surface with time, the effects of FBC bottom ash on DC and WC conditions may also reflect this loss due to cumulative rain applied at the time of the rainfall of interest.

Our results show that the positive effect of FBC bottom ash on reducing erosion and runoff was longer-lasting with increasing amount of illite or smectite in the soil. On highly weathered soils, the effect of increasing ionic strength of the infiltrating and overland flowing water on erosion and runoff was dependent on soil type: no effect on an eroded kaolinitic soil (Cecil eroded), short-lasting effect on a high clay Oxisol (Molokai), or negative effect on a sandy loam Oxisol (not included in this study). The FBC bottom ash effectiveness on variable charge soils was dependent on soil pH, its buffer capacity, and flocculation. Similarly, studies conducted by Stern et al. (1991) showed that soils that did not contain smectite are more stable and less susceptible to crust formation, whereas soils that contained smectites, even in small amounts, are susceptible to sealing and sensitive to electrolyte changes in soil solution and are affected by phoshygypsum spread on the soil surface. In soils where physicochemical forces are more important than the mechanical effects involved in consolidation and reorientation of clay particles, a change in either type or concentration of electrolyte in the pore fluid will drastically affect void ratio (Olson and Mesri, 1970). Olson and Mesri (1970) also suggest that physicochemical effects dominate in high surface area smectitic soils, whereas in sand, muscovite, and kaolinite soils which have low surface areas, mechanical effects are dominant; in illite soils, which have an intermediate surface area, physicochemical and mechanical effects both operate. Our data suggest that physicochemical and mechanical effects on sealing, although complementary, may be dependent upon clay mineralogy and surface charge characteristics.

CONCLUSIONS

Sediment yield as a function of intensity (or runoff) was well described by power law equations. As the soil eroded and consolidated, a smaller exponent was obtained, suggesting a lesser influence of intensity (or runoff) on erosion. The DC condition was the most erodible condition for half of the cases. It is postulated that shrinking of the soil disrupts aggregates and pre-formed crust, forming new aggregates but possibly with lower stability. Rewetting of DC soil increased runoff rates possibly through reduction in the surface seal permeability, but rain on WC soil did not increase runoff. With increasing amounts of smectite or illite, a longer-lasting effect of FBC bottom ash was observed; thus suggesting that this material has great potential for reducing sealing and erosion on permanent charge soils. Kaolinitic soils were more stable, generating lower runoff and soil loss rates, and response of these soils to FBC bottom ash was dependent on flocculation and surface charge characteristics.

ACKNOWLEDGMENTS

The senior author acknowledges the financial support by Rotary International and CNPq, Brazil. The authors are indebted to Dr. Rob J. Loch from Queensland Department of Primary Industries, Australia, and Dr. Christopher Smith from USDA Soil Conservation Service, Hawaii, for assisting in the collection and shipment of soil samples.

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